A New Multi-Energy Neutrino Radiation-Hydrodynamics Code in Full General Relativity and Its Application to Gravitational Collapse of Massive Stars

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Gravitational collapse of massive stars initiate supernovae that are one of the most bright objects in the universe. The mechanism of core-collapse supernovae is not clarified yet though the steady progress of supernova simulations. We explain two reasons. (i) Supernovae are not reproduced in a simple numerical setup. (ii) The ultimate simulations that employ all required physical ingredient, have not been performed although we sometimes observe explosions in the simulations under a relatively realistic situations.

An huge energy of 10^{53} ergs is released when an iron core of a massive star collapses and become a neutron star. A portion of the energy is used to push a shock wave that are generated at that time and propagates from the center to the outer region. The shock experience strong cooling via the process of photo-dissociation of iron, that is inverse process of the nuclear fusion. An important lesson of one dimensional (1D) spherically symmetric simulations is that the shock stalls at 150 km due to the cooling process [1].

Recently two dimensional (2D) or three dimensional (3D) simulations are performed thanks to the development of super-computers [2]. In this setup, we can employ effect of convection: some matters go upward while the others go downward. We observe shock revivals in the setup since the convection promotes neutrino heating process. While the neutrino takes the thermal energy away in the vicinity of the neutron stars, that gives thermal energy to the matter in outer region. The convection efficiently conveys the thermal energy given by the neutrino heating to the vicinity of the shock where the energy is required to revive the shock. The convection relaxes the condition of the neutrino luminosity required to the shock revival by 30–50 %.

The next problem arises. How reliable are such multi-dimensional simulations? Unfortunately the results of the simulation strongly depends on their input physics. Different groups show different results even if they use same progenitor models. To solve the problem, we should construct ultimate models which employ all physical knowledge we have. For the purpose, we developed a new code that solve multi-group neutrino transport under fully general relativistic framework [3].

In Fig. 1, we compare our new methods with the previous work. We evaluate the methods with 4 axises. Left top is dimensionality of hydrodynamics and right top is schemes employed to solve the radiation-hydrodynamics. Right bottom is sophistication level of micro-physics i.e. the number of neutrino reactions considered in the simulation. Left bottom is treatment of the gravity. Our new code (red) [3] takes high score in the diagram compared to the previous works [1,2]. We can obtain most reliable results with the new code.

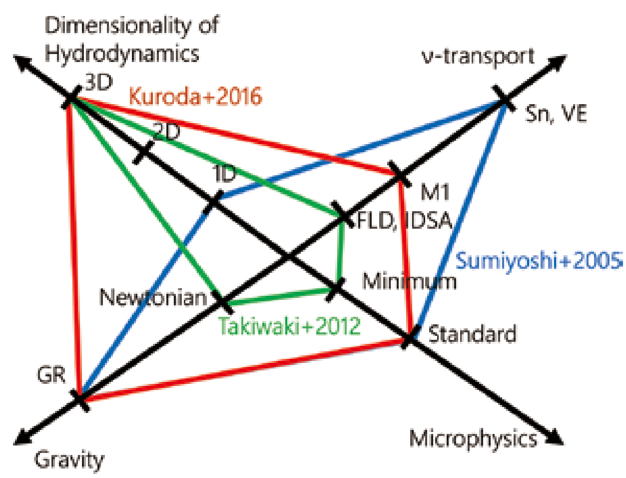

Figure 1: Comparison of the method used in supernova simulations.

References

[1] Sumiyoshi, K., Yamada, S., Suzuki, H., et al.: 2005, *ApJ*, **629**, 922.
[2] Takiwaki, T., Kotake, K., Suwa, Y.: 2012, *ApJ*, **749**, 98.
[3] Kuroda, T., Takiwaki, T., Kotake, K.: 2016, *ApJS*, **222**, 20.